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Constitutive Model Parameter Study for Armor Steel and Tungsten Alloys

by Stephen J. Schraml

ARL-RP-351 **January 2012**

A reprint from the *Society for Experimental Mechanics 2011 Annual Conference and Exposition on Experimental and Applied Mechanics,* Uncasville, CT, 13–16 June 2011.

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Abstract

A computational parametric study was performed to assess the influence of the selection of Johnson-Cook constitutive model parameters on the numerical simulation of tungsten rods penetrating rolled homogeneous armor (RHA) steel targets. The parameter space involved two sets of Johnson-Cook model parameters for RHA, two sets of Johnson-Cook parameters for the tungsten rod material, four tungsten rod length-to-diameter (L/D) ratios, and two continuum mechanics codes. Striking velocities considered in the study ranged from approximately 1000 – 2000 m/s. The study revealed that no single combination of Johnson-Cook model parameters provides superior overall prediction of penetration depth over the other possible combinations across the full range of rod L/D considered. The study provides valuable guidance on the selection of material model parameters future studies of kinetic energy penetration.

1 Introduction

Numerical simulation is used extensively in the development of explosive warheads, kinetic energy (KE) penetrators, and armors to defeat such threats [1]. Simulations, when combined with judicious use of experimentation, can provide valuable insight into complex weapon/target interactions that is not possible through experimentation alone. The physics of shock wave propagation through various types of media, high-rate behavior of materials, and material failure are all essential characteristics of such interactions that must be captured in the computational methods.

This paper documents an extensive computational study to assess the influence of existing Johnson-Cook [2] constitutive model parameters on the simulation of tungsten rods penetrating rolled homogeneous armor (RHA) steel targets. One of the initial goals of the effort was to identify a "best possible" combination of tungsten and RHA model parameters to use for simulations across a wide range of conditions of interest to the development of KE penetrators and armor systems that are effective against KE penetrators. The study considered tungsten rods with length-to-diameter (L/D) ratios of 5, 10, and 15, and striking velocities of approximately 1000 – 2000 m/s. The study also included an L/D=30 rod at a striking velocity of 1500 m/s.

The metric used to evaluate the computational results was total penetration depth normalized by penetrator length (P/L). The computational results were compared to experimental data in the case of rods of L/D=5, 10, and 15. For the L/D=30 rods, the simulation results were compared to an empirical fit to an experimental database.

The study results revealed that no single combination of Johnson-Cook constitutive model parameters produces the best penetration depth results across the full range of parameters considered. However, the study

does provide guidance on the use of constitutive model parameters when operating within the parameter space considered. This work also provides a foundation for additional study to include the evaluation of additional constitutive models, fracture models, etc.

2 Johnson-Cook Constitutive Model

The Johnson-Cook constitutive model describes the flow stress (σ) of a metal as a function of plastic strain (ε_p), plastic strain rate ($\dot{\varepsilon}_p$), and temperature (T), as defined in equations 1 and 2. In this model, the terms A, B, C, n and m are model parameters (constants), T_{melt} is the melt temperature of the material, T_{room} is the ambient temperature, and $\dot{\varepsilon}_0$ is a reference plastic strain rate. The model parameters are typically derived from material characterization experiments through a fitting process intended to reproduce the trends observed in the characterization experiments while minimizing error.

$$\sigma = \left(A + B\varepsilon_p^n\right)\left(1 + Cln\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\left(1 - T'^m\right) \tag{1}$$

$$T' = \frac{T - T_{room}}{T_{melt} - T_{room}} \tag{2}$$

2.1 RHA Model Parameters

RHA steel is a commonly used material in armor systems and ballistic testing. It is also a *de facto* standard in the assessment of ballistic performance. Penetration performance of KE penetrators, explosively formed penetrators, and shaped charge jets is typically described in terms of their depth of penetration into a thick stack of RHA target plates. Furthermore, the protection capability of an armor system is typically described in terms of “RHA equivalence” which typically represents the areal density of the armor system relative to the equivalent areal density of RHA that would be required to have the same level of protection. For these reasons, the ability to accurately model the performance of RHA in ballistic events is critical to many penetrator and armor development programs.

RHA is available in a variety of plate thicknesses from 6.4 mm (1/4 inch) to 152 mm (6 inches). As a result of the rolling process, thinner plates are observed to have a higher surface hardness than thicker plates. Meyer & Kleponis [3] provide an empirical relationship between RHA plate thickness and quasi-static yield strength based on experiments by Benck [4]. A common practice in modeling RHA in numerical simulations is to set the A parameter of the Johnson-Cook model according to this relationship. This practice was employed throughout the study described here.

Two different sets of Johnson-Cook constitutive model parameters for RHA were evaluated in this study [3, 5]. The Meyer & Kleponis parameters were derived from material characterization tests performed by Gray et al. [6] on 50.8-mm-thick RHA plates. The Weerasooriya & Moy parameters were developed from their own characterization tests on RHA plates ranging in thickness from 19.0 mm to 76.2 mm [7]. Like Benck, Weerasooriya & Moy observed that the quasi-static yield strength varied with plate thickness, further validating the approach of varying the A parameter in the Johnson-Cook model in accordance with the

RHA plate thickness.

Figure 1 provides a plot of flow stress vs. plastic strain at room temperature for the two sets of parameters for a quasi-static yield strength of 746 MPa which corresponds to a plate thickness of 63.5 mm. In this figure, the thin lines represent quasi-static ($\dot{\varepsilon}_p$=0.002/s) deformation and the thick lines represent high-rate ($\dot{\varepsilon}_p$=3000/s) deformation.

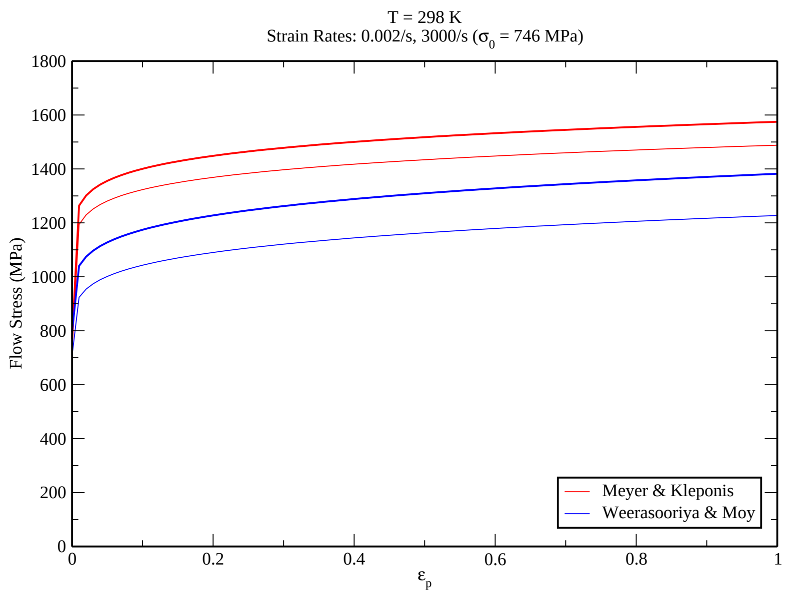

Figure 1. Flow stress at ambient temperature for 63.5-mm-thick RHA.

The curves in figure 1 illustrate the differences between the two sets of RHA parameters. The Meyer & Kleponis parameters and the Weerasooriya & Moy parameters produce similar work hardening behavior. Even though the trends are similar, the flow stress produced by the Weerasooriya & Moy parameters is less than that of the Meyer & Kleponis parameters. The gap between the thin (quasi-static) and thick (high-rate) curves for each parameter set indicate the rate hardening effect. The Weerasooriya & Moy parameter set has a larger C coefficient than the Meyer & Kleponis set, resulting in a slightly larger gap between the thin and thick curves.

2.2 Tungsten Model Parameters

Two tungsten penetrator materials were considered in the study. The first consisted of 90% tungsten (W), 7% nickel (Ni), and 3% iron (Fe) by volume and is denoted by 90W-7Ni-3Fe. The second consisted of 93% tungsten, 5% nickel, and 2% iron (93W-5Ni-2Fe). The Johnson-Cook parameters for these materials were derived by Johnson & Cook [2] and Weerasooriya [8], respectively.

A plot of flow stress as a function of plastic strain at room temperature for the two tungsten material parameter sets is provided in figure 2. As in figure 1, the thin lines represent quasi-static deformation and the thick lines represent high-rate deformation. The curves in figure 2 show that 90W-7Ni-3Fe parameter set produces negligible work hardening as compared to 93W-5Ni-2Fe. This is a result of significantly greater

B and n parameters for the 93W-5Ni-2Fe parameters as compared to 90W-7Ni-3Fe. The rate hardening effect produced by the 93W-5Ni-2Fe parameters is also greater as a result of the larger C parameter and is evidenced by the greater gap between the quasi-static and high rate curves as compared to the gap between the 90W-7Ni-3Fe curves.

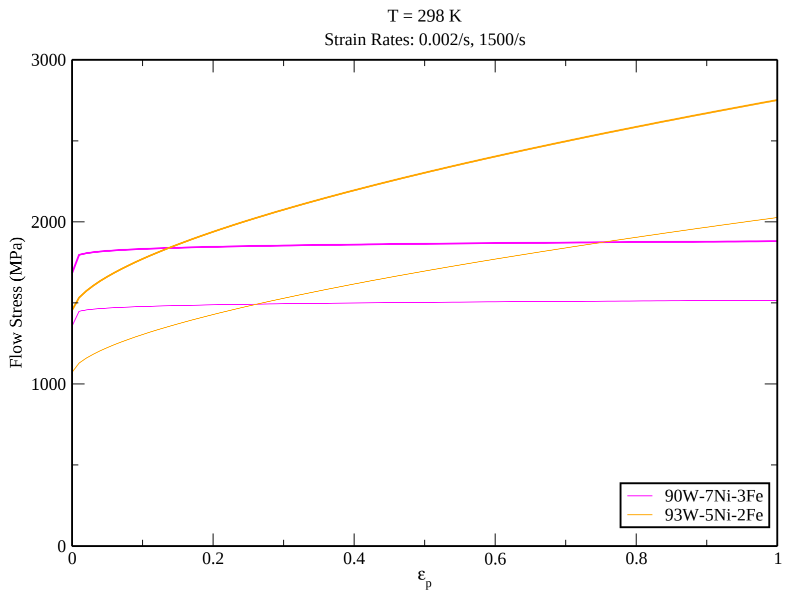

Figure 2. Flow stress at ambient temperature for 90W-7Ni-3Fe and 93W-5Ni-2Fe.

3 Penetration Experiments

The goal of the study was to examine the trends in simulated penetration performance for each combination of tungsten and RHA Johnson-Cook parameter set across a wide variety of striking velocities and rod L/D. To this end, experimental data were obtained for rod L/Ds of 5, 10, and 15. The L/D=5 results were obtained from experiments by Enderlein [9] in which tungsten rods were fired into a stack of four RHA target plates at 0 degrees obliquity. The rods were right circular cylinders and were 100 mm long with a diameter of 20 mm. The target plates were each 63.5 mm thick.

The L/D=10 and 15 experimental data were obtained from experiments by Magness [10]. In these experiments, 93W-5Ni-2Fe tungsten rods with hemispherical noses were fired into 152-mm cubes of RHA at 0 degrees obliquity. In all the L/D=10 and 15 experiments, the rods were machined to have a constant mass of 65 g.

Experimental data were not used for the study of rods with L/D=30. Instead, the computational results were evaluated through comparison to an empirical expression for P/L. Lanz & Odermatt [11] developed this empirical relationship for penetration performance for rod L/D ranging from 11 to 32 and striking velocities ranging from 1100 to 1900 m/s. The current study considered only one striking velocity for L/D=30 (1500 m/s). Using the relationship derived by Lanz & Odermatt, the expected P/L is 0.836 for the L/D=30 rod with a striking velocity of 1500 m/s.

4 Numerical Simulations

Two continuum mechanics codes were used in the computational study. CTH [12] is an Eulerian finite volume code for modeling solid dynamics problems involving shock wave propagation, multiple materials, and large deformations in one, two, and three dimensions. CTH employs a two-step solution scheme – a Lagrangian step followed by a remap step. The conservation equations are replaced by explicit finite volume equations that are solved in the Lagrangian step. The remap step uses operator-splitting techniques to replace multidimensional equations with a set of one-dimensional equations. High-resolution material interface trackers are available to minimize material dispersion.

The arbitrary Lagrangian-Eulerian code ALE3D [13] is the other continuum mechanics code used in the study. ALE3D uses a hybrid finite element and finite volume formulation in an unstructured grid. ALE3D is a multi-physics code with features to support simulations involving wave propagation, material deformation and fracture, heat conduction, chemical kinetics, and magneto-hydrodynamics. Simulations involving modest amounts of deformation can be run Lagrangian, in which the unstructured mesh follows the material motion. For cases of larger deformation, advection can be employed to allow the mesh to relax in order to prevent tangling. It is possible to run an ALE3D simulation as an Eulerian simulation (i.e. in the same manner that CTH operates) by employing an advection step after each Lagrangian step and relaxing the mesh to its original position. All ALE3D simulations in this study were performed in this way.

A common set of characteristics was employed in all simulations in the study. The simulations were performed in two dimensions with a rectangular computational domain of uniform mesh resolution throughout. The mesh resolution was defined such that there were 10 computational cells/elements across the radius of the penetrator. A shock-particle velocity equation of state (EOS) was used for all materials in the simulations and a common set of EOS parameters was defined for all simulations. Similarly, the Johnson-Cook fracture model [14] was employed for for all materials in the simulations and a common set of fracture model parameters was employed in all cases.

The study involved the use of Johnson-Cook constitutive model parameters for two different tungsten rod materials. The different volume percentages of tungsten in each resulted in different densities. The density used in the study was 17.346 g/cm^3 for 90W-7Ni-3Fe and 17.7 g/cm^3 for 93W-5Ni-2Fe.

The simulations involving the L/D=5 rod used the dimensions and cylindrical geometry that were described previously. As a result, the 90W-7Ni-3Fe and 93W-5Ni-2Fe rods in the L/D=5 simulations had slightly different masses. For the L/D=10 and 15 rods, the hemispherical nose geometry was defined to reproduce the same 65-g rod mass that was used in the experiments. In this case, the 90W-7Ni-3Fe and 93W-5Ni-2Fe rods had identical masses but slightly different dimensions.

Because no experimental data were used for evaluation of the L/D=30 simulations, a notional rod geometry was employed. In this case, the rod mass was defined as 130 g with a hemispherical nose, resulting in rods that were approximately equal in diameter and double in length to the L/D=15 rods. The resulting L/D=30 rods were nominally 6.8 mm in diameter and 204 mm long.

5 Results and Discussion

Simulations were performed to replicate the L/D=5, 10, and 15 experiments. For each experiment, a family of simulations was performed such that every combination of continuum code (CTH and ALE3D), RHA parameter set (Meyer & Kleponis and Weerasooriya & Moy), and tungsten rod material parameter set (90W-7Ni-3Fe and 93W-5Ni-2Fe) were employed, resulting in eight simulations for each experimental measurement. Comparison of the simulation results to the experimental data are provided in the following subsections.

5.1 Results for L/D=5

Comparison of the L/D=5 simulations to the experimental results are provided in figure 3. This figure contains four plots in two rows and two columns. Each is a plot of P/L as a function of striking velocity. The plots are arranged with the 90W-7Ni-3Fe results in the left column and the 93W-5Ni-2Fe results in the right column. The ALE3D results are in the top row and the CTH results are in the bottom row.

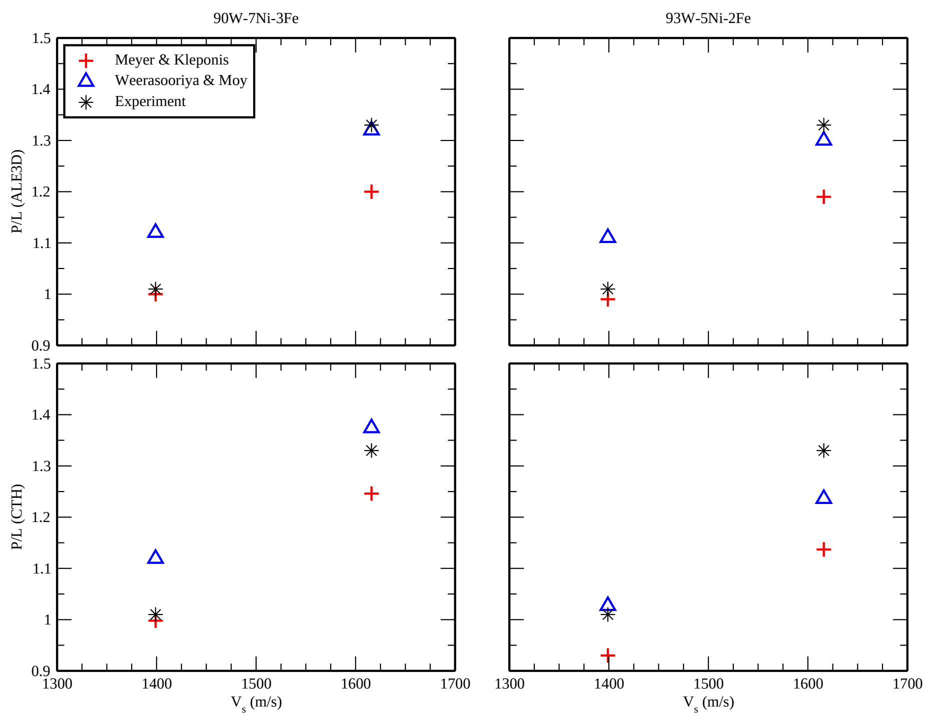

Figure 3. Study results for L/D=5.

Common characteristics and trends are observed across all four plots in figure 3. The P/L results from the Weerasooriya & Moy parameter set are consistently greater than that of the Meyer & Kleponis set. This is a result of the overall greater strength flow strength produced by the Meyer & Kleponis parameter set. No single combination of continuum code, tungsten parameter set, and RHA parameter set matches the trend in change of P/L with increasing velocity.

An interesting trend observed in the L/D=5 study results is the lower simulated P/L from the 93W-5Ni-2Fe parameter set as compared to the results from the 90W-7Ni-3Fe set. One would expect 93W-5Ni-2Fe to yield a greater P/L because of its higher density (and therefore greater rod mass in the case of the constant-geometry L/D=5 rod). It appears that the difference in P/L between the two tungstens is a result of the difference in the Johnson-Cook model parameters. In figure 2, the 93W-5Ni-2Fe parameter set exhibited more strain hardening than 90W-7Ni-3Fe, but had a lower flow stress in the lower range of plastic strains ($\varepsilon_p < 0.25$).

Because of the limited availability of experimental data for L/D=5, the computational results do not yield a single set of parameters that provide a best match to the experimental results.

5.2 Results for L/D=10

The study results for L/D=10 are provided in figure 4. In this figure, the four plots are presented in the same 2X2 format as the L/D=5 results. The L/D=10 results show the Meyer & Kleponis parameters provide the best overall comparison to the experimental data. As in the L/D=5 results, the 93W-5Ni-2Fe tungsten parameter set produced a lower P/L than 90W-7Ni-3Fe and the P/L from the Weerasooriya & Moy RHA parameter set was consistently greater than that of Meyer & Kleponis.

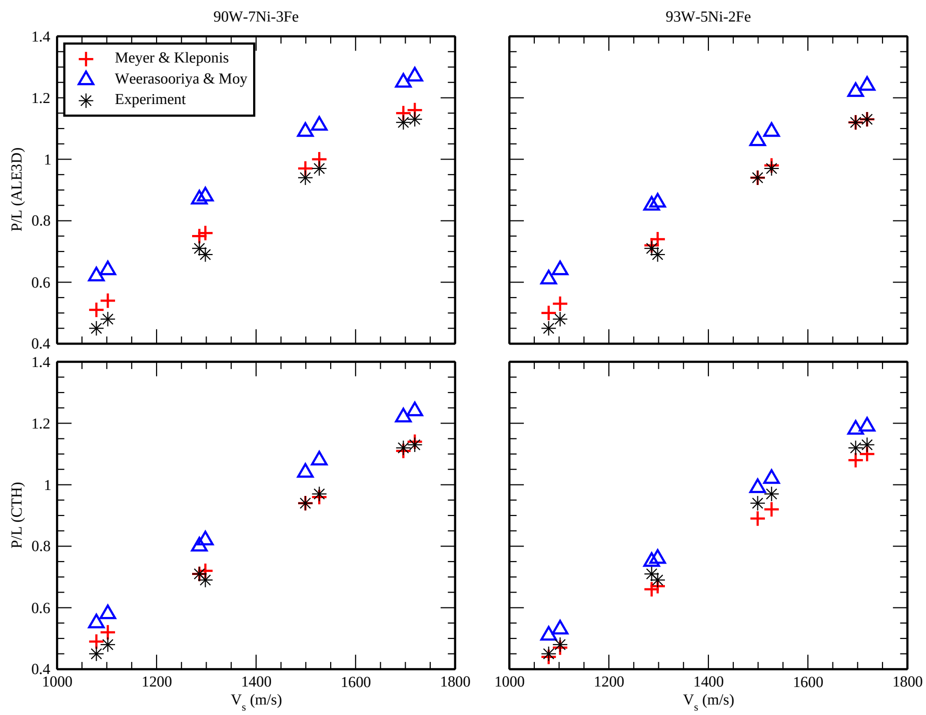

Figure 4. Study results for L/D=10.

5.3 Results for L/D=15

The results for the L/D=15 simulations are presented in figure 5. The qualitative observations of these results are consistent with those of the L/D=5 and 10 results. Overall, all combinations of continuum code, tungsten parameter set, and RHA parameter set result in simulation results that capture the overall trends of the experimental data. Between the two RHA parameter sets, Meyer & Kleponis appears to provide the best overall comparison to the experiments.

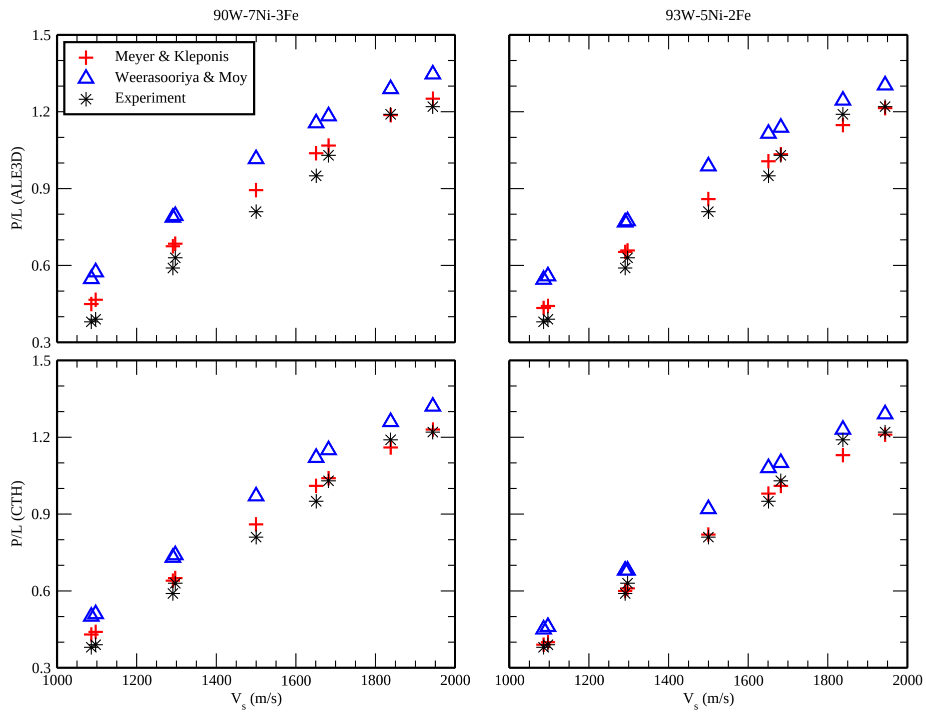

Figure 5. Study results for L/D=15.

5.4 Summary of Results for L/D=5, 10, & 15

The presentation of the study results in figures 3, 4, and 5 provides a valuable qualitative comparison of the simulation results to the experimental data. These comparisons clearly illustrate the influence of the model parameters on the simulation results. However, these plots alone do not provide the quantitative information required to rank the simulation results for the purpose of selecting the best possible combination of parameter sets for simulating tungsten penetration of RHA.

To obtain this quantitative measure, the sum of squares of the errors (SSE) of the simulation results compared to the experimental results was performed. In this analysis, an SSE measure was obtained for every combination of continuum code, tungsten parameter set, and RHA parameter set. The results of this analysis are summarized in table 1. These results show that for three of the four combinations of continuum code and tungsten parameter set, Meyer & Kleponis produces the lowest SSE of the two RHA parameter sets. As a result of this quantitative analysis and the trends observed in figures 3, 4, and 5, the Meyer & Kleponis

parameter set is found to provide the best overall results for rods with L/D in the range of 5 to 15.

Table 1. Sum of Squares of Errors for L/D=5, 10, & 15.

RHA Parameter Set	ALE3D		CTH	
	90W-7Ni-3Fe	93W-5Ni-2Fe	90W-7Ni-3Fe	93W-5Ni-2Fe
Meyer & Kleponis	0.0723	0.0445	0.0260	0.0589
Weerasooriya & Moy	0.4682	0.3496	0.2172	0.0941

5.5 Results for L/D=30

Simulations were performed for the L/D=30 rods for a striking velocity of 1500 m/s. The simulation results were evaluated by comparison to an empirical model result of P/L=0.836. For each simulation, the percentage error of P/L was calculated relative to the empirical model. The results in table 2 show that the Weerasooriya & Moy RHA parameter set produces more accurate results than Meyer & Kleponis. This contradicts the results of the L/D=5, 10, and 15 rods described earlier in which Meyer & Kleponis generally produced more accurate results than the other two.

Table 2. P/L Errors for L/D=30 Simulations.

RHA Parameter Set	P/L Error (%)			
	CTH		ALE3D	
	90W-7Ni-3Fe	93W-5Ni-2Fe	90W-7Ni-3Fe	93W-5Ni-2Fe
Meyer & Kleponis	-13.7	-14.9	-6.1	-11.4
Weerasooriya & Moy	2.0	1.5	7.3	2.1

6 Summary

This paper documents a computational study to identify the influence of the selection of Johnson-Cook constitutive model parameters on the penetration performance of tungsten rods into RHA steel targets in numerical simulations. The study encompassed two sets of model parameters for RHA, two sets for the tungsten rod material, two different continuum mechanics codes, four different rod L/Ds, and striking velocities ranging from 1000 – 2000 m/s. The original intent of the study was to identify an optimum set of tungsten and RHA model parameters for use in numerical simulations over a wide range of initial conditions.

The study revealed that no single combination of model parameters provided the best overall predictive capability over the entire range of rod L/D considered. The RHA parameter set by Meyer & Kleponis produced the best comparison to experimental penetration data for rods of L/D from 5 to 15. However, for rods of L/D=30, this parameter set yielded the least accurate computational results.

Even though this study did not yield an overall optimum set of RHA and tungsten Johnson-Cook parameters, it has provided valuable guidance in selection of model parameters for a variety of rod L/Ds.

References

1. K.D. Kimsey, S.J. Schraml, and E.S. Hertel. Scalable Computations in Penetration Mechanics. *Advances in Engineering Software*, 29(3–6):209–215, 1998.

2. G.R. Johnson and W.H. Cook. A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures. In *Ballistics*, The Hague, The Netherlands, 1983. Seventh International Symposium on Ballistics.

3. H.W. Meyer and D.S. Kleponis. An Analysis of Parameters for the Johnson-Cook Strength Model for 2-in-Thick Rolled Homogeneous Armor. Technical Report ARL-TR-2528, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, June 2001.

4. R.F. Benck. Quasi-Static Tensile Stress Strain Curves – II, Rolled Homogeneous Armor. Technical Report BRL-MR-2703, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, November 1976.

5. T. Weerasooriya and P. Moy. RHA Constitutive Model – Function of Hardness. Unpublished, April 2010.

6. G.T. Gray, S.R. Chen, W. Wright, and M.F. Lopez. Constitutive Equations for Annealed Metals Under Compression at High Strain Rates and High Temperatures. Technical Report LA-12669-MS, Los Alamos National Laboratory, NM, 1994.

7. T. Weerasooriya and P. Moy. Effect of Strain Rate on the Deformation Behavior of Rolled Homogeneous Armor (RHA) Steel at Different Hardnesses. Proceedings of the 2004 SEM International Congress and Exposition on Experimental Mechanics. Costa Mesa, CA, June 2004.

8. T. Weerasooriya. Deformation Behavior of 93W-5Ni-2Fe at Different Rates of Compression Loading and Temperatures. Technical Report ARL-TR-1719, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, July 1998.

9. M.W. Enderlein. Armor Backpack Effectiveness Against Rod Penetrators at Ordnance Velocities. Technical Report BRL-MR-3939, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1991.

10. L.S. Magness. *A Phenomenological Investigation of the Behavior of High-Density Materials Under the High Pressure, High Strain Rate Loading Environment of Ballistic Impact*. PhD thesis, Johns Hopkins University, 1992.

11. W. Lanz and W. Odermatt. Penetration Limits of Conventional Large Caliber Anti Tank Guns/Kinetic Energy Projectiles. In *Ballistics*, Stockholm, Sweden, 1992. 13th International Symposium on Ballistics.

12. J.M. McGlaun and S.L. Thompson. CTH: A Three-Dimensional Shock Wave Physics Code. *International Journal of Impact Engineering*, 10:351–360, 1990.

13. A.L. Nichols. Users Manual for ALE3D: An Arbitrary Lagrange/Eulerian 2D and 3D Code System. Technical Report LLNL-SM-433954, Lawrence Livermore National Laboratory, Livermore, CA, June 2010.

14. G.R. Johnson. Status of the EPIC Codes, Material Characterization and New Computing Concepts at Honeywell. In *Computational Aspects of Penetration Mechanics*, New York, 1982. Springer-Verlag.

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	R BANTON
	S KUKUCK

INTENTIONALLY LEFT BLANK.